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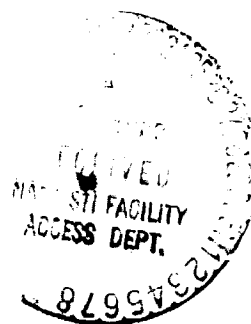
# The Future of High Energy Gamma Ray Astronomy and its Potential Astrophysical Implications

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**August 1982**

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**THE FUTURE OF HIGH ENERGY GAMMA RAY  
ASTRONOMY AND ITS POTENTIAL ASTROPHYSICAL IMPLICATIONS**

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# THE FUTURE OF HIGH ENERGY GAMMA RAY ASTRONOMY AND ITS POTENTIAL ASTROPHYSICAL IMPLICATIONS

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## I. INTRODUCTION

The promise of high energy ( $\geq 10$  MeV) astrophysics as a valuable new avenue for the exploration of the universe is now beginning to be realized. In the years to come, satellites should carry instruments which will have over an order of magnitude greater sensitivity than those flown thus far. These detectors should also have improved energy and angular resolution. The information to be obtained from these experiments should greatly enhance our knowledge of several astrophysical phenomena including: the very energetic and nuclear processes associated with compact objects, the structure of our galaxy, the origin and dynamic pressure effects of the cosmic rays, the high-energy particles and energetic processes in other galaxies, and the degree of matter-antimatter symmetry of the universe. The relevant aspects of galactic high energy  $\gamma$ -ray astronomy will be discussed by Giovanni Bignami at this conference: The extragalactic phenomena will be emphasized in this paper along with the instruments planned for the future. The high energy  $\gamma$ -ray results of these forthcoming programs such as GAMMA-I and the Gamma Ray Observatory will almost certainly provide justification for even more sophisticated telescopes. These advanced instruments might be placed on the Space Station currently being considered by NASA.

## II. EXTRAGALACTIC GAMMA RAY ASTROPHYSICS

Less is known about extragalactic  $\gamma$  radiation than galactic, but on the basis of our present knowledge and theoretical studies, the potential scientific importance of what is expected to be achievable with the next generation of satellite instruments is very high. In this section, both normal and active galaxies of several types and the extragalactic diffuse radiation will be discussed in terms of the current knowledge, its theoretical interpretation, and what might be expected.

### (a) Normal Galaxies

In the context of the discussion here, normal galaxies compose a very broad category which includes most galaxies and, in particular, elliptical galaxies, normal spirals, barred spirals, and all their variations. It specifically excludes those galaxies which are of an exceptional nature in luminosity or variability in at least one wavelength region, such as Seyfert galaxies, quasars, BL Lacertae objects, and intense radio galaxies. There has been no normal galaxy beyond our own seen in high energy  $\gamma$  rays thus far, but, as will be seen, this is not surprising based on the emission level of our own galaxy.

To determine the intensity of  $\gamma$ -ray emission that might be expected from another galaxy similar to our own, it seems reasonable to determine the luminosity of our own galaxy and then to estimate how the galactic luminosity might vary with mass. The  $\gamma$ -ray luminosity calculated for our galaxy is not very sensitive to the particular model. Calculations of Bignami et al. (1975), Strong and Worrall (1976), Kniffen et al. (1977), and Caraveo and Paul (1979) based on the observed galactic  $\gamma$ -ray intensity give estimates for the luminosity of our galaxy above 100 MeV in the range  $(0.9 \text{ to } 1.3) \times 10^{42}$  photons  $\text{s}^{-1}$ . Thus, unless our concept of the Galaxy is quite wrong, a value of  $1.0 \times 10^{42}$  photons ( $E_\gamma > 100 \text{ MeV}$ )  $\text{s}^{-1}$  should have a reasonable probability of being within a factor of two of the  $\gamma$ -ray luminosity of the Galaxy. The corresponding energy emission for  $E_\gamma > 100 \text{ MeV}$  is  $\sim 5 \times 10^{38} \text{ ergs s}^{-1}$  which is similar to that in the radio and X-ray regions, but several orders of magnitude smaller than that in the optical band.

Since it is assumed that the production processes involved are the same in other galaxies, the energy spectra for other normal galaxies are expected to be similar to that in our own. However, estimating the luminosity of another galaxy requires a bit more caution and probably should not even be attempted for galaxies differing from our own in stellar mass by a very large factor. The high energy  $\gamma$ -radiation arises both from interactions of cosmic rays with matter and photons and from point sources, with the former seeming, at present, to be the larger contributor. If another galaxy is a flat disk with the same matter density as ours, has cosmic rays like ours, and is simply bigger or smaller, the  $\gamma$ -ray luminosity would most likely just scale as the mass of the diffuse matter since it is the local emitting density which appears to determine the local cosmic ray density. (See e.g., Fichtel and Trombka, 1981.) However, if the other galaxy were as big as ours and had a flat disk like ours, but its matter density were very different, the cosmic rays would be proportional to the density since they can ultimately be held by gravitational attraction only. The cosmic-ray intensity everywhere then, and hence the luminosity would scale as the square of the mass. Since less massive galaxies are generally smaller, the first alternative seems closer to the typical case and is a less extreme assumption.

The question of the number of  $\gamma$ -ray point sources as a function of galactic mass is clearly speculative, and, depending on the theories of formation, many conclusions could be reached. For simplicity, it will be assumed that the number of point sources is proportional to the mass of the galaxy to the first power or a bit larger. It is also possible that another type of galaxy, such as an ellipsoidal one, might have few sources of cosmic rays. Answers to these and other questions await future experimental study.

Based on considerations of this sort, Fichtel and Trombka (1981) have estimated the intensity of some of the closest galaxies under the assumption that the intensity relative to our own is between that which would be obtained assuming proportionality to mass and the square of the mass. Three normal galaxies were found to be large enough in angular dimensions and to be expected to be intense enough not only to allow their detection, but to permit a measure of the  $\gamma$ -ray distribution with the next generation of orbiting high energy  $\gamma$ -ray instruments, in particular the high energy  $\gamma$ -ray telescope on GRO. These galaxies are the Large Magellanic Cloud,  $\sim 8^\circ$  in extent, the Small Magellanic Cloud and M31,  $\sim 4^\circ$  in diameter. The intensities are estimated to be  $(2 \text{ to } 7) \times 10^{-7}$ ,  $(1 \text{ to } 3) \times 10^{-7}$  and  $(0.5 \text{ to } 1) \times 10^{-7}$  photons ( $E_\gamma > 100$

MeV)  $\text{cm}^{-2} \text{s}^{-1}$  respectively. A few other galaxies in our local group are likely to be detectable, but either their size or distance prohibits hope of any detailed structural studies.

#### (b) Active Galaxies

Active galaxies, including Seyfert galaxies, radio galaxies, quasars, and BL Lacertae objects, are far less common than ordinary galaxies, but have a far greater luminosity. For at least two of the four active galaxies for which positive  $\gamma$ -ray results exist (Centaurus-A, NGC 4151, MCG 8-11-11, and 3C 273), as much or more energy is emitted in the  $\gamma$ -ray region ( $E > 0.1$  MeV) than in the radio, optical, or X-ray range.

The  $\gamma$ -rays observed from the Seyfert galaxies NGC 4151 and MCG 8-11-11 are of low energy, and only upper limits to the high energy  $\gamma$  radiation exist, as shown in Figures 1 and 2. The spectra are similar in that both show a marked increase in the spectral slope at about the same energy. The several measurements shown in the low energy  $\gamma$ -ray region for NGC 4151 (Figure 1) were made at different times, and, assuming no significant errors in the data, clearly show a time variability. For five other Seyferts (and also several other emission line galaxies) upper limits derived from the SAS-2  $\gamma$ -ray data (Bignami et al., 1979) are substantially (more than an order of magnitude) below an extrapolation of the power law X-ray spectra (Mushotzky et al., 1979), suggesting that a sharp spectral change in the low-energy  $\gamma$ -ray region may be a general feature of these galaxies.

Turning to quasars, 3C 273 is the brightest X-ray quasar and is the only quasar which has been clearly identified as a source of high energy ( $> 100$  MeV)  $\gamma$ -rays (Swanenburg et al., 1978). The spectrum of 3C 273 steepens sharply from the X-ray range to the  $\gamma$ -ray region, as shown in Figure 3, with the slope of the differential energy spectrum changing from 1.4 in the hard X-ray region to 2.7 in the high energy  $\gamma$ -ray region. The upper limit in the very high energy  $\gamma$ -ray interval ( $3 \times 10^8$  to  $3 \times 10^9$  keV), also shown in the figure, is consistent with the steep spectrum continuing to these energies. The change in spectral shape between the hard X-ray and  $\gamma$ -ray region seen for 3C 273 is similar to that suggested for the Seyfert galaxies for which data exist. The COS-B instrument has observed 3C 273 in July, 1976, June, 1978, and June-July, 1980, and no significant variation in the  $\gamma$ -ray fluxes between the observations was observed (Bignami et al., 1981 and Hermsen et al., 1981).

The closest known quasar is 2S 0241+622, but it is very close to the galactic plane ( $b = 2^\circ$ ). The error box of the COS-B  $\gamma$ -ray source CG 135+1 (Hermsen et al., 1977) contains the position of 2S 0241+622, and the possible association has been pointed out by Apparao et al. (1978). Because of the large area of the  $\gamma$ -ray error box as well as the alternative explanation of a  $\gamma$ -ray source within the galaxy, this identification must be considered uncertain.

BL Lacertae objects are now generally thought to be galaxies which are possibly similar to, but less intense than, quasars. Of the objects in this class, two, Markarian 421 and 501, have been clearly identified as X-ray sources (Scharwartz et al., 1978; Marshall and Jernigan, 1978), and others have tentative identifications as X-ray emitters. The X-ray spectra of Mk 421

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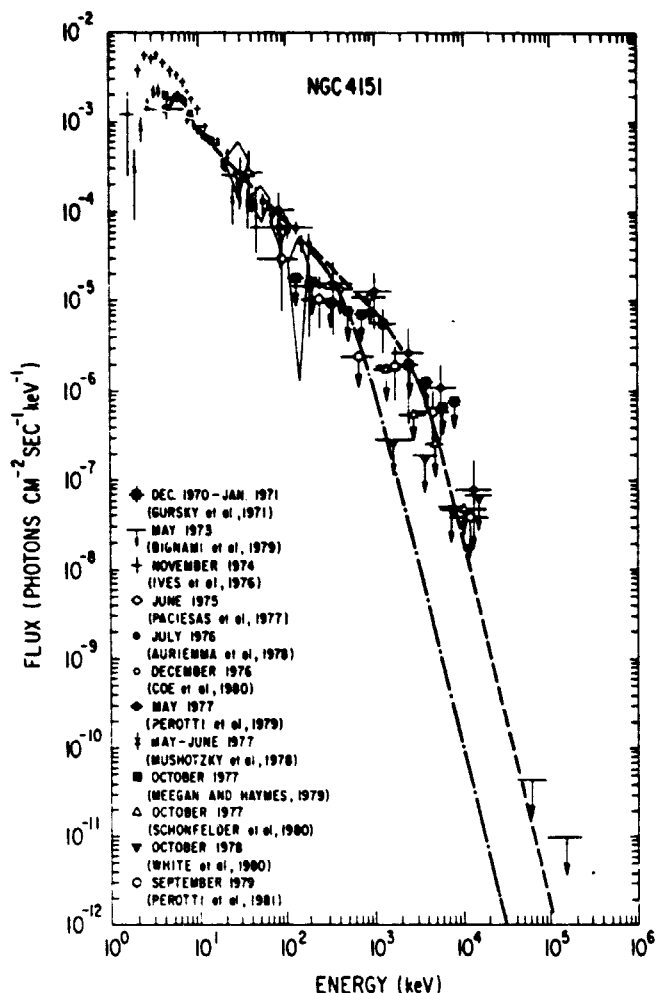


Fig. 1: The differential X and  $\gamma$  ray spectral results from several experiments as a function of energy for NGC 4151. The curves are given by the equation  $I = 0.8 \times 10^{-2} / E^{1.0} [1 + (E/E_0)^{3.0}]$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$  with  $E$  in keV, where  $E_0 = 3 \times 10^3$  for the dashed curve and  $E_0 = 1 \times 10^3$  for the dot-dash curve. (See Fichtel and Trombka, 1981).

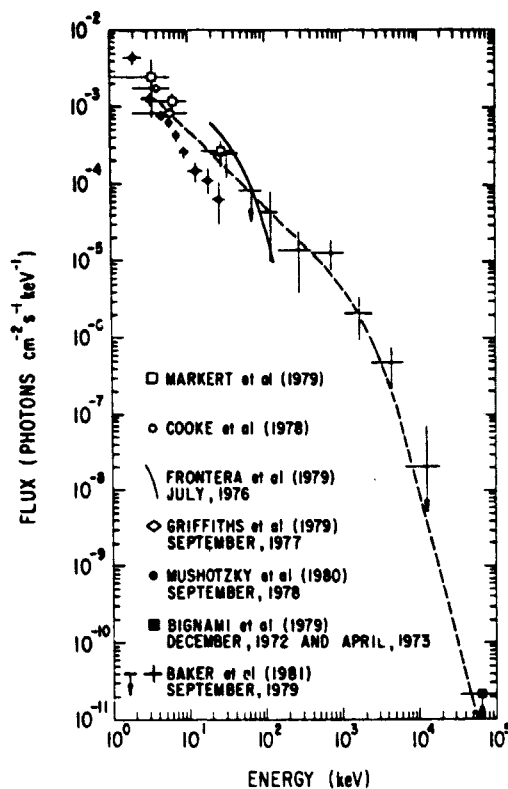


Fig. 2: The differential X and  $\gamma$  ray spectral results from several experiments as a function of energy for MCG 8-11-11 (redrawn from Baker et al., 1981). The curve is given by the equation  $\phi = 0.5 \times 10^{-2} / [E^{1.0} \{1 + (E/E_0)^{3.0}\}]$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$  with  $E$  in keV and  $E_0 = 3 \times 10^3$ .

and Mk501 show no absorption and have photon power law spectral indexes of  $0.9 \pm .5$  and  $1.2 \pm .2$ , respectively (Mushotzky et al., 1978a). Even if the steepest allowable spectrum (index  $\sim 1.4$ ) is used, extrapolation to the 100 MeV range predicts intensities roughly an order of magnitude above the upper limits reported by Bignami et al. (1979) for these two objects. Thus, their spectra must also have a significant steepening somewhere between 50 keV and 35 MeV. The six-fold reduction in intensity observed for Mk 421 over a period of 6 months (Mushotzky et al., 1979) could affect this conclusion. However,

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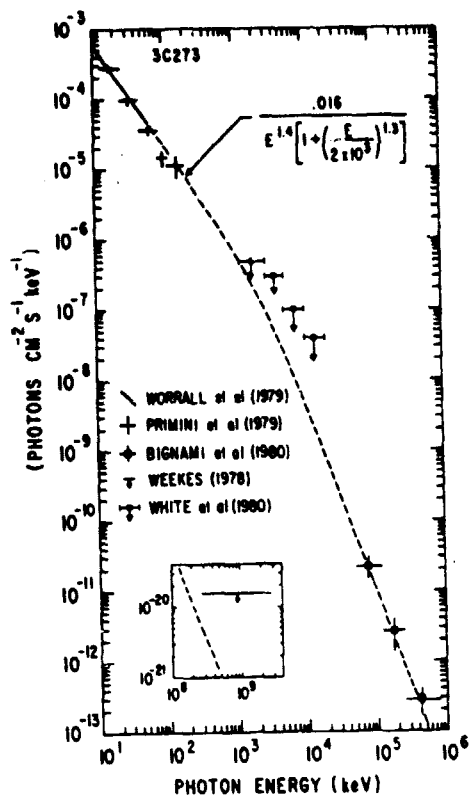


Fig. 3: The differential high energy photon spectral results from several experiments as a function of energy for 3C 273. The dashed curve is given by the equation shown in the figure.

at present it seems that BL Lacertae objects also have a marked change in spectral slope between the hard X-ray and the higher energy  $\gamma$ -ray region.

Centaurus-A (NGC 5128), generally believed to be the closest radio galaxy, is the only other active galaxy that has been seen in  $\gamma$  rays. It has now been observed in all frequency bands from radio through low energy  $\gamma$ -rays (e.g., Hall et al., 1976, and Baity et al., 1981) and, although  $\gamma$ -ray emission is not seen in the 30 to  $10^3$  MeV region (Bignami et al., 1979), a strong indication of very high energy ( $E > 3 \times 10^{11}$  eV)  $\gamma$ -ray emission has been found (Grindlay et al., 1975). As seen in Figure 4, the observations of the radiation from CEN-A in the X-ray region through the high energy  $\gamma$ -ray region again suggest a spectral steepening between the hard X-ray and the high energy ( $\sim 100$  MeV)  $\gamma$ -ray region. The very high energy ( $> 10^{11}$  eV) observation falls at a level below a straight line extrapolation between the X-ray spectral measurements and the high energy  $\gamma$ -ray upper limits, but well above the extrapolation of a function such as the one shown in Figures 1, 2, and 3.

It should also be noted that CEN-A demonstrates considerable intensity variations in the radio region and in the moderate and hard X-ray range, where its variation has been nearly an order of magnitude and may be accompanied by substantial changes in spectral shape (Beall et al., 1978; Mushotzky et al., 1978a).

There is no general agreement on the nature of active galaxies or how similar or different they are. It has been suggested frequently that all have massive

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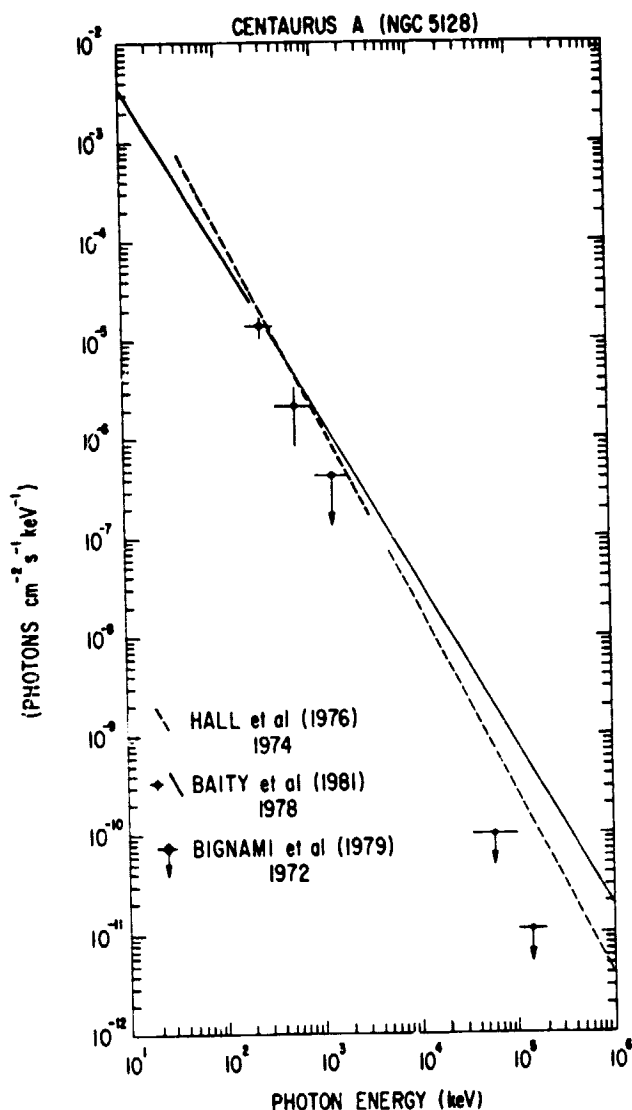


Fig. 4: Observed X-ray and  $\gamma$ -ray spectral data for Centaurus A. The light solid and dashed lines are extrapolations of the X-ray data for comparison to the high energy  $\gamma$ -ray upper limits.

(of the order of  $10^8 M_\odot$ ) black holes at their centers. Alternatively, it has been postulated that, whereas quasars and BL Lacertae objects may be similar, Seyfert and radio galaxies may be rather different. There are a large number of suggestions for the origin of the high energy radiation. With the greater energy involved relative to a normal galaxy, it would seem reasonable that much greater numbers of high energy particles should be produced. Also, active galaxies are expected to have very large magnetic fields and photon densities, especially near the center. Some of the possible origin mechanisms for  $\gamma$ -ray emission will now be considered.

In the conditions thought to exist in the vicinity of the core of an active galaxy, synchrotron radiation and Compton radiation could become quite important, and the radiation from the synchrotron process itself might even create enough photons for the Compton process to become important between the

parent electrons and the secondary photons (e.g., Grindlay, 1975; Shapiro and Salpeter, 1975; Mushotzky, 1976; Maraschi and Treves, 1977; and Baity et al. 1981). These Compton-synchrotron models generally predict a break in the energy spectrum between the X-ray and the high energy  $\gamma$ -ray energy ranges, based on the observation of a break in the synchrotron spectrum between the radio and optical energy ranges for many active galaxies. Earlier in this section, it was seen that several types of active galaxies may have this general type of spectral shape.

There is, however, another possible phenomenon to keep in mind. High energy photon-photon interactions may become quite important near the center of active galaxies, depleting the number of high energy  $\gamma$  rays. The astrophysical significance of high energy  $\gamma$ -ray absorption in dense photon regions associated with active galaxies was first noted by Jelly (1966), and developed by others such as Herterich (1974), primarily for stellar objects, and Rees (1978). In a region with a high electron and hard X-ray photon density, X-rays and  $\gamma$ -rays are created through Compton radiation and possibly bremsstrahlung in great numbers. The photon density then could be such that  $\gamma$ -rays with energies much above  $m_e c^2$  interact frequently with X-rays leading to pair production. The resulting electrons and positrons lose energy through Compton interactions which enhance the X-ray and even the hard X-ray component. The positrons ultimately combine with electrons and annihilate each other, creating photons near  $1/2$  MeV. Assuming that there is a sufficiently hard X-ray photon density in the beginning, a marked increase in spectral slope will result near 1 MeV and there will be a relative dearth of very high energy photons. The photon region just below one MeV could actually be enhanced. As already seen here, this type of spectrum, i.e., one which is relatively flat in the hard X-ray region and dramatically steeper in the  $\gamma$ -ray region, is quite consistent with the data for at least some active galaxies.

There is still another process which can produce a spectrum with a marked change in slope near 1 MeV. For massive ( $\geq 10^8 M_\odot$ ) black holes, Leiter and Kafatos (1978) and Kafatos and Leiter (1979) note that large energy releases may occur as the result of Penrose quantum processes occurring in the ergosphere of a massive black hole. In this model, hard X-rays and  $\gamma$ -rays fall toward the massive black hole gaining a very substantial amount of energy. They then interact with electrons and protons moving tangentially in what is sometimes called an accretion layer. In particular, a low energy infalling  $\gamma$ -ray may scatter off an electron ("Penrose-Compton Scattering"), inject the electron into the black hole, and escape as a blueshifted  $\gamma$ -ray with an energy as large as  $\sim 4 m_e c^2$ . If there is a spread in energies, as there would be in an astrophysical situation, the resulting energy spectrum would have a marked increase in spectral slope near a few  $m_e c^2$ , again as observed.

There is an additional interesting aspect to this theory. When the infalling photon is blueshifted to an energy of from tens of MeV to tens of GeV, it may scatter off a proton and produce an electron-positron pair that subsequently escapes with a higher energy. This process is called "Penrose pair production." The high energy electrons may then produce higher energy  $\gamma$ -rays through the processes already discussed.

Several authors (Eichler, 1979; Silberberg and Shapiro, 1979, and Berezhinsky and Ginzburg, 1981) have argued that matter accreting onto a black hole may

surround it with a shell sufficiently thick to prevent the escape of any significant flux of  $\gamma$  rays. There is substantial debate over just how thick the matter is, but Morris (1982) has done calculations to show that it must be quite thick. For representative spectra the  $\gamma$ -ray flux falls to 1/2 its value after  $20 \text{ gm cm}^{-2}$  and does not reach 1/10 its value until about  $100 \text{ gm cm}^{-2}$ . Further, if there are relativistic electrons as there are in most of these models, the flux produced by the electrons through bremsstrahlung reaches a maximum at  $10\text{--}30 \text{ gm cm}^{-2}$  for typical spectra and does not fall to 1/10 the maximum until  $200\text{--}300 \text{ gm cm}^{-2}$ . For energetic nuclei the corresponding thicknesses are even larger. Thus, a shell of more than several hundred  $\text{gm cm}^{-2}$  is necessary to reduce significantly a  $\gamma$ -ray flux.

Further, as noted by Bassani and Dean (1981) and Morris (1982), jets, from active galaxies which have them, presumably must form tunnels through any shell of surrounding gas. A beam of  $\gamma$  rays may be emitted through such a tunnel as well. Rather complex considerations of such tunnels are possible including guiding of relativistic particles by the magnetic fields. Actual  $\gamma$ -ray enhancement through charged particle interactions with matter, photons, and fields are easily possible.

These various mechanisms have been incorporated into a variety of models for active galaxies. Without further experimental evidence on the spectral shape, intensity, time variations, possible correlation with jets, and other considerations, it seems difficult to test and sort the theories. Having seen four active galaxies in  $\gamma$ -rays and considering the general prediction of the theories, with the improvement of over an order of magnitude in sensitivity over the entire  $\gamma$ -ray range that will be forthcoming with GRO, it is reasonable to expect that the  $\gamma$ -ray emission from enough active galaxies will be measured with GRO to be able to form meaningful conclusions regarding the mechanisms for the production of high energy  $\gamma$  rays and to add substantially to our knowledge of the nature of active galaxies.

### (c) Diffuse Extragalactic Radiation

At energies above 10 MeV, the first measurements related to an extragalactic diffuse radiation were those of Kraushaar and Clark (1962), whose upper limits from Explorer 11 provided an experimental refutation of the steady-state theory of cosmology, which predicted a quite high intensity resulting from matter-antimatter annihilation. Several other upper limits were reported from early balloon experiments, with the first suggestion of a diffuse high energy flux coming from the OSO-3 satellite experiment, Kraushaar, et al. (1972). However, it was data from the SAS-2 high energy  $\gamma$ -ray experiment that clearly established a high energy extension of the diffuse radiation with a steep energy spectrum above 35 MeV (Fichtel et al., 1977; and Fichtel, Simpson, Thompson, 1978).

It is very desirable to consider the entire  $\gamma$ -ray energy interval in discussing the extragalactic diffuse radiation. However, the intensity in the region from about 1/2 to 10 MeV, where there is a substantial local background resulting from cosmic ray interactions leading to excited nuclei, has been quite controversial. There are a very large number of early results in this energy region representing either upper limits or reported positive results with large uncertainties (see, for example, Figure 9-2 of Fichtel and Trombka, 1981 or Schönfelder, 1982) for a summary of these data). The analyses of

Trombka et al. (1977) and Daniel and Lavakare (1975) have indicated that many of the early reported positive results in this energy range were too high because of the failure to eliminate all the background from the measurements. At present, the final results from Apollo 15 and 16  $\gamma$ -ray detectors (Trombka et al., 1977), which were on a boom of variable length, and the recent work of Schönfelder et al. (1980) are generally accepted as a good representation of the diffuse energy spectrum in the intermediate energy range. Although lower in intensity than the earlier reported spectra, the spectrum still shows a small "hump" in the spectrum near 2 MeV.

The analysis of the data in the high energy ( $E_\gamma > 35$  MeV) region also deserves special mention not because of any significant detector or locally produced background, which can be very small in a carefully designed experiment like SAS-2, but because of the need to separate the galactic diffuse radiation from the general diffuse radiation being discussed here. Several different approaches have been used to perform this separation on the SAS-2  $\gamma$ -radiation data including a comparison of  $1/\sin b$  (Fichtel et al., 1977), analyses wherein other galactic radiation such as the 21 cm line and the 150 MHz brightness temperature were compared with the  $\gamma$  radiation (Fichtel, Simpson, and Thompson, 1978), and a study of the  $\gamma$ -ray intensity as a function of galaxy counts and a combination of galaxy counts and a  $(1/\sin b)$  function (Thompson and Fichtel, 1982). The last approach to determining the diffuse radiation at high energies was an attempt to approximate the physical situation believed to exist for the galactic diffuse radiation as closely as possible. From work by Puget et al. (1976), Lebrun (1979), and Lebrun et al. (1981), galaxy counts appear to have emerged as a good tracer of the total (atomic and molecular) gas column density in the local region of the galaxy and hence should give a good measure at high latitudes of the combined nucleon-nucleon and bremsstrahlung component, assuming the cosmic ray density in the plane is reasonably uniform locally and its scale height is uniform. Making the same assumptions for the cosmic rays,  $(1/\sin b)$  might be a better representation for the Compton component than the galaxy count approach, since the photon distribution is believed to be more uniform over its relative large scale height compared to that for the matter. Thompson and Fichtel (1982) have shown that a good correlation is achieved between these parameters and the  $\gamma$ -ray intensity, as shown in Figures 5 and 6. All approaches discussed here give the same result for the spectrum within uncertainties, namely a steep spectrum which extrapolates readily back through the measured low energy  $\gamma$ -ray intensities to the results determined in the X-ray region, as shown in Figure 5.

Although the diffuse spectral measurements are reasonably self-consistent, the degree of spatial isotropy is not well known. At low  $\gamma$ -ray energies ( $\sim 1$  MeV), Trombka et al. (1977) estimate that the anisotropic component from galactic sources does not exceed 20 percent of the total flux. At higher energies (35 to 100 MeV), the center-to-anticenter ratio for the radiation with  $20^\circ < |b| < 40^\circ$  was measured to be  $1.10 \pm 0.19$  and that perpendicular to the galactic plane intensity to that in the  $20^\circ < |b| < 40^\circ$  region was measured by Fichtel, Simpson, and Thompson (1978) to be  $0.87 \pm 0.09$ ; each of these results is, of course, consistent with isotropy to within errors. Although much more precise measures of the isotropy are clearly desired, no evidence for a major anisotropy exists. In particular, the high energy  $\gamma$ -ray results just quoted eliminate a spherical galactic halo origin for the radiation in view of the Sun's great distance from the galactic center. In

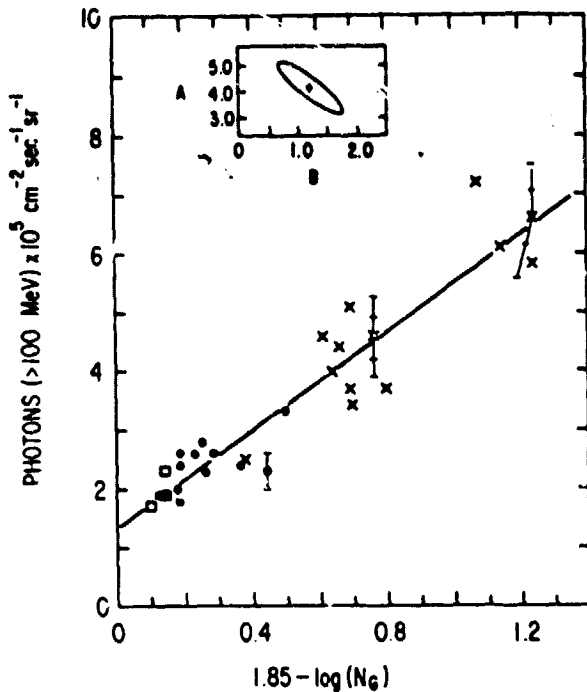
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Fig. 5: The  $\gamma$ -ray intensity above 100 MeV measured by SAS-2 as a function of galaxy counts (Thompson and Fichtel (1982)).

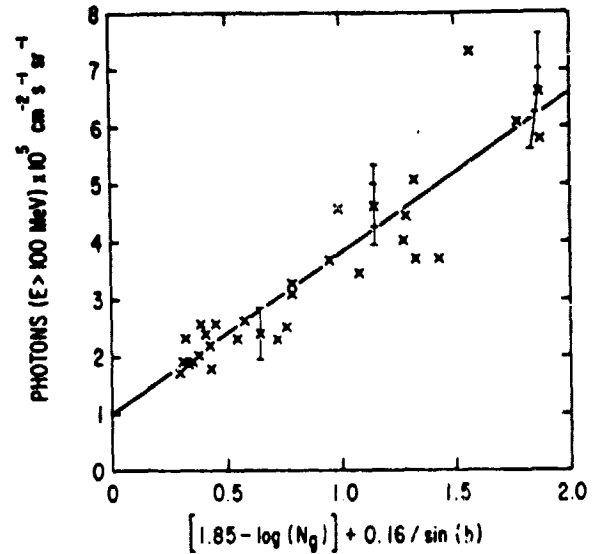


Fig. 6: The  $\gamma$ -ray intensity above 100 MeV measured by SAS-2 as a function of  $[1.85 - \log(N_g) + 0.16 / \sin(b)]$ . The double error bars refer to the total uncertainty and the statistical uncertainty only.

the future trying to establish the level of isotropy, or deviations therefrom, on both a coarse scale and a fine scale will be quite important.

A large number of theories predicting a diffuse  $\gamma$ -ray background have appeared in the literature over the years. With the measurements of the spectrum and intensity which now exist and which have been presented here, most of these seem not to be likely candidates for the majority of the diffuse radiations (see, for example, Fichtel and Trombka, 1981). Two possibilities seem to remain at present and will be discussed here.

One of these involves a baryon-symmetric universe, containing superclusters of galaxies of matter and others of antimatter. The annihilation of nucleons and antinucleons at the boundaries (Stecker, Morgan, and Bredekamp, 1971) leads to a  $\gamma$ -ray spectrum consistent with the observations. The normalization is selected to have the curve agree with the data, but it is consistent with the currently accepted possible range of densities between clusters. Generally, this theoretical model predicts a smooth distribution over the sky; however, a test of this theory (in addition to a precise measure of the energy spectrum) could be the detection of fairly small enhancements in the  $\gamma$  radiation in the direction of boundaries between close superclusters of galaxies.

The other possibility for the explanation of the diffuse extragalactic radiation which seems to be a reasonable candidate is the sum of the radiation from point sources and particularly active galaxies integrated over

cosmological times. This concept that the diffuse high energy celestial radiation, and particularly the  $\gamma$  radiation, might result from active galaxies has been proposed by several authors (e.g., Strong and Worrall, 1976; Bignami et al., 1978; Schönfelder, 1978; Grindlay, 1978; and Bignami et al., 1979). An accurate estimate of the expected radiation is hampered by the lack of measured  $\gamma$  ray spectrum from active galaxies.

Using the data on the few known objects, Bignami et al. (1979) and Fichtel and Trombka (1981) conclude that it is quite conceivable that Seyfert galaxies and Quasars could account for the diffuse  $\gamma$  radiation using conservative evolutionary models. Not only the intensity, but also the spectral shape, considering how little is known, are not unreasonable. The results derived by Fichtel and Trombka (1981) are shown in Figures 7 and 8. In determining the

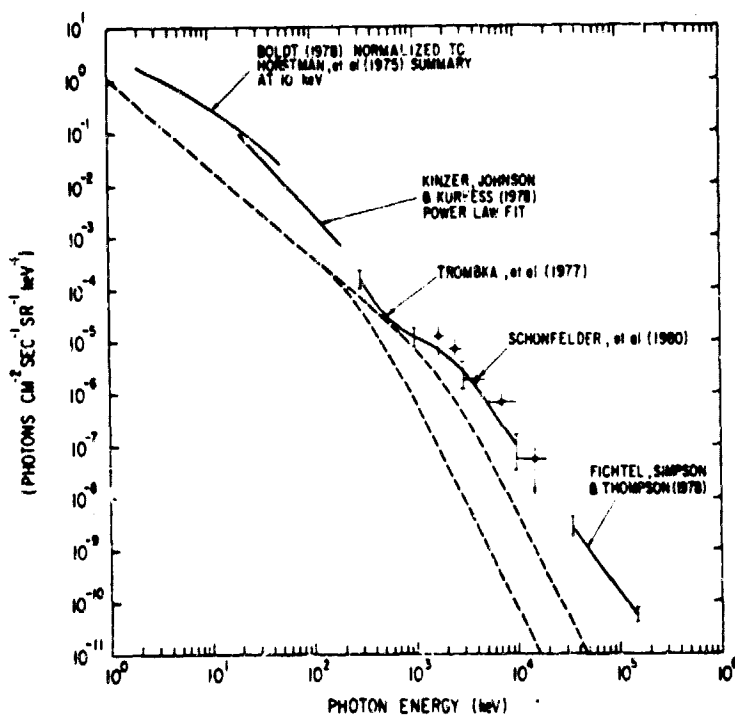


Fig. 7: The diffuse  $\gamma$ -ray energy spectrum estimate for Seyfert galaxies under the assumptions described briefly in the text and more completely by Fichtel and Trombka (1981), from whom the figure is taken, compared to some of the more recent experimental data.

intensity of the diffuse radiation to be expected from active galaxies, they used the standard Friedman world model with zero pressure and zero cosmological constant, and absorption processes were neglected, as is justified in the  $\gamma$ -ray and hard X-ray region. They also assumed that  $Q_1$ , the emissivity of a galaxy of type 1, had the form

$$Q_1(E(1+z), z) = Q_1(E(1+z)) f(z) \quad (1)$$

wherein the source function retains the same form and the evolutionary factor is separable. For Seyfert galaxies, they used the two spectral shapes shown in Figure 1 of this paper as a normalization deduced from the Seyferts observed in hard X-rays, a Seyfert density of  $1 \times 10^{-5} \text{ Mpc}^{-3}$ , a  $Z_{\text{max}}$  of 4, and an  $f(z)$  of 1 (i.e., no evolution). For the quasars, they assumed the spectrum shown in Figure 3, an average intensity half that of 3C 273, a number density law for quasars of

$$\rho = \rho_0 \exp(\beta \tau) \quad (2)$$

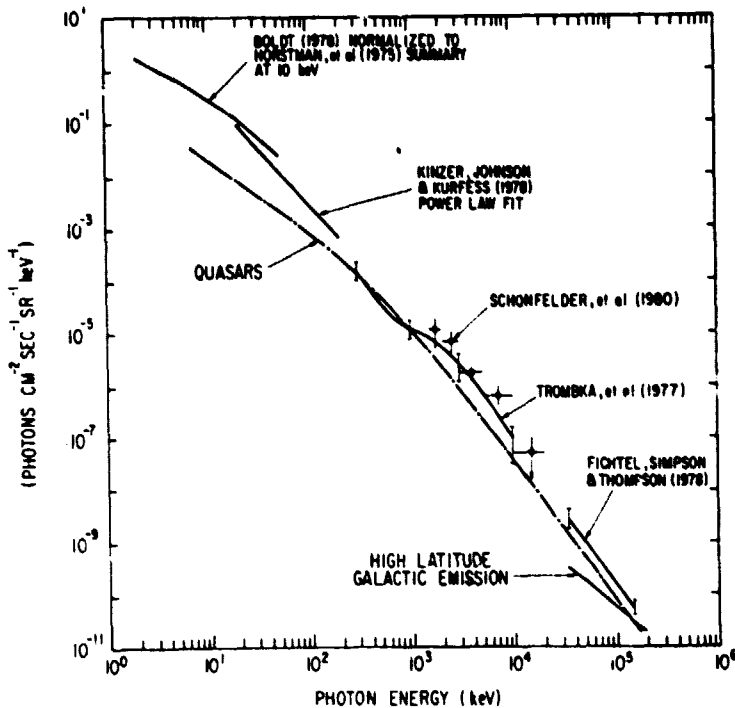


Fig. 8: The diffuse  $\gamma$ -ray energy spectra estimated for quasars under the assumptions described briefly in the text and more completely by Fichtel and Trombka (1981), compared to some of the more recent experimental data.

with  $\beta = 10$ ,  $\rho_0 = 0.1 \text{ Gpc}^{-3}$ , and  $\tau$  the lookback time as a fraction of the age of the universe. In both cases,  $H_0$  and  $q_0$  were taken to be  $60 \text{ km s}^{-1}$  and  $0.05$ , respectively.

For illustrative purposes, one specific theoretical concept for active galaxies will be mentioned. Leiter and Boldt (1982) have proposed a model based on supermassive Schwarzschild black holes with accretion disks radiating near the Eddington luminosity limit. At early stages, precursor active galaxies would primarily emit thermal X-rays, their emission being due to thermal accretion onto a massive Kerr black hole. In the process of disk accretion, the black hole will eventually be spun-up to a canonical Kerr black hole with an equilibrium value of  $a/M=0.998$ . By then, the inner region of the hot accretion disk has effectively penetrated the Penrose target region causing the Penrose Compton scattering of the disk X-rays into MeV  $\gamma$ -rays. In addition to this component, which is predominately below a few MeV, there would be a second component consisting of the  $\gamma$  radiation emitted in a synchrotron self-Compton process by the relativistic electrons accelerated by the disk-dynamo system. In this model, the observed high energy  $\gamma$  radiation would be due to the latter mechanism and the intermediate energy "bump" at about 3 MeV, seen in Figures 7 and 8, would be due to the Penrose process and would be variable. The authors believe that, if this theory is correct, there would be detectable variations in the diffuse radiation in small elements of the sky ( $10 \text{ deg}^2$ ) over several days in the 1/2 to 3 MeV region, giving a specific test for this theory.

Regarding the possibility of further information on the high energy extragalactic diffuse  $\gamma$  radiation being forthcoming in the near future, there will probably be none beyond that of SAS-2 until GRO is in orbit. The

combination of the full cosmic ray intensity unsurpressed by the Earth's magnetic field and more material somewhat displaced from the plastic scintillator shield prevented measurements on this low level extragalactic radiation by COS-B. Similar factors are likely to prevent GAMMA-I from making these measurements. The high energy  $\gamma$ -ray telescope to fly on GRO, however, has been designed with the measurement of the diffuse extragalactic radiation specifically in mind, and the approximately twenty times increase in sensitivity should permit a major step forward in this area.

### III. FUTURE MISSION PROSPECTS

The major satellite opportunities for high energy  $\gamma$ -ray astronomy in the 1980's are the GAMMA-I and the Gamma Ray Observatory. The  $\gamma$ -ray instruments to be carried on these satellites will be described in the next two subsections. The information to be obtained from these instruments may be supplemented by results from  $\gamma$ -ray balloon flights and from yet to be approved spacelab and small satellite opportunities. In the more distant future, the Space Station which is only in the planning stage at NASA may provide opportunities to fly quite large  $\gamma$ -ray instruments which might be refurbished or reconfigured in space.

#### (a) GAMMA-I

The next  $\gamma$ -ray satellite expected to fly is GAMMA I, which should be launched in about two years on a Soviet satellite. It is similar to SAS-2 and COS-B in the sense that its central element is a multilayer spark chamber system, triggered by a directional counter telescope, and surrounded on the upper end by an anticoincidence system as shown in Figure 9. The sensitive area is about  $1600 \text{ cm}^2$  or about  $2 \frac{2}{3}$  times that of SAS-2 or COS-B; the area solid angle factor is about the same because the viewing angle is smaller. It has an energy-measuring calorimeter which should be able to measure energies with significantly better accuracy than the energy-measuring element of COS-B. The  $\gamma$ -ray arrival direction will also be measured with greater accuracy. The upper spark chamber system is a twelve-level wide gap Vidicon system. The directionality of the electrons is determined by a time-of-flight system rather than a directional Cerenkov counter. The time-of-flight system approach to the directional measurement, which will also be used in the high-energy  $\gamma$ -ray telescope to be flown on the GRO, has proved to be an order of magnitude more efficient in rejecting undesired events than the previously used directional Cerenkov systems. Because of the space required, it could not have been incorporated in the earlier missions, even if the low power spaceflight quality electronic had been developed.

Consideration is being given to adding a coded aperture at the top of the instrument to attempt to improve angular resolution. Accelerator tests are to be undertaken during 1983 to determine if the angular resolution is in fact improved in consideration of the loss in sensitivity, the restricted geometry, and the increase in background.

The improved sensitivity and  $\gamma$ -ray directional accuracy relative to earlier missions should allow better definition of the characteristics of part of the

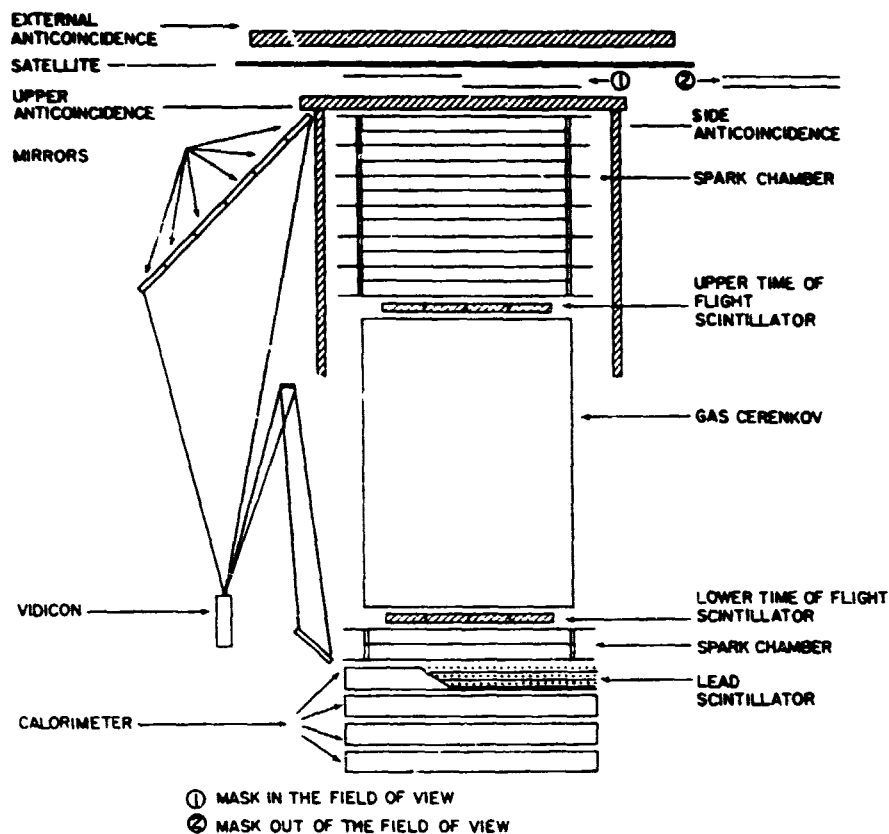


Fig. 9: The GAMMA-I Instrument

galactic plane and provide better position information on many or most of the localized excesses already observed, as well as possibly adding to the number of observed extragalactic sources.

GAMMA-I is a joint effort of nine institutions, the Space Research Institute of Moscow (IKI), the Physical Engineer Training Institute of Moscow (MIFI), P.N. Lebedev Physics Institute of Moscow (FIAN), A.F. IOFFE Physical Technical Institute of Leningrad (FTI), Section d'Astrophysique du CEA/Saclay (IRF/DPhG/AP), Centre d'Etude Spatiale des Rayonnements (CESR), Istituto di Fisica Cosmica of Milano, Istituto di Astrofisica Spaziale at Frascati, Istituto TESRE at Bologna.

#### (b) The Gamma Ray Observatory

The Gamma Ray Observatory (GRO) is an approved NASA mission with a launch tentatively planned for 1988. There are four instruments covering the energy range from 0.03 MeV to  $3 \times 10^4$  MeV, with a major increase in sensitivity over previous satellite experiments. The scientific goals of this mission can be summarized as follows:

A study of the dynamic, evolutionary forces in compact objects such as neutron stars and black holes, as well as  $\gamma$ -ray emitting objects whose nature is yet to be understood.

A search for evidence of nucleosynthesis - the fundamental building process in nature - particularly in the environment of supernovae.

The exploration of our galaxy in the  $\gamma$ -ray range particularly with regard to regions difficult to observe at other wavelengths, the origin and dynamic pressure effects of the cosmic rays, and structural features particularly related to high-energy particles.

The study of the nature of other galaxies in the high-energy realm and especially the extraordinary ones such as radio galaxies, Seyfert galaxies, and quasars.

The study of cosmological effects through the detailed examination of the diffuse radiation and the search for primordial black hole emission.

These scientific goals necessarily require a set of large instruments, since several are required to cover the entire energy range, and all must have a significant increase in size over earlier satellite instruments to achieve the desired increase in sensitivity. It is advantageous to combine the required instruments into one mission not only because they place similar requirements on a spacecraft, but also because of the very great scientific value of studying the entire  $\gamma$ -ray spectrum of any object at the same time to examine in detail the nature of time variations.

The combined compliment of instruments to be incorporated into the Gamma Ray Observatory is expected to have the capability to carry out the following:

A survey of high energy  $\gamma$ -ray sources and diffuse emission with a point source sensitivity of  $10^{-7}$  photon  $\text{cm}^{-2} \text{sec}^{-1}$  or better, angular resolution of about  $0.1^\circ$  for strong sources, and energy resolution around 15% at energies above  $\sim 10^2$  MeV.

A survey of  $\gamma$ -ray sources and diffuse emission with sensitivities around  $10^{-5}$  photon  $\text{cm}^{-2} \text{sec}^{-1}$  and energy resolution around 10 percent at energies between 0.1 and 30 MeV.

Detection and identification of nuclear gamma lines with an energy resolution of  $< 0.4$  percent and sensitivity of the order of  $5 \times 10^{-5}$  photon  $\text{cm}^{-2} \text{sec}^{-1}$ . The initial subjects of observation will be the interstellar medium and supernova shells.

Observations of  $\gamma$ -ray bursts, including studies of their spectral and temporal behavior.

The Gamma-Ray Observatory, shown in Figure 10, will be a shuttle-launched, free-flyer satellite. The nominal circular orbit will be about 400 kilometers with an inclination of  $28.5^\circ$ . The spacecraft will be capable of accommodating approximately 5500 kilograms of instruments and supplying 600 watts of experiment power. The 17 kilobits per second of experiment data will be supported via NASA's Tracking and Data Relay Satellite system. Celestial pointing to any point on the sky (excluding the Sun) will be maintained to an accuracy of  $\pm 0.5^\circ$ . Knowledge of the pointing direction will be determined to an accuracy of 2 arc minutes so that this error contributes negligibly to the overall determination of the direction of  $\gamma$ -ray source. Absolute time will be

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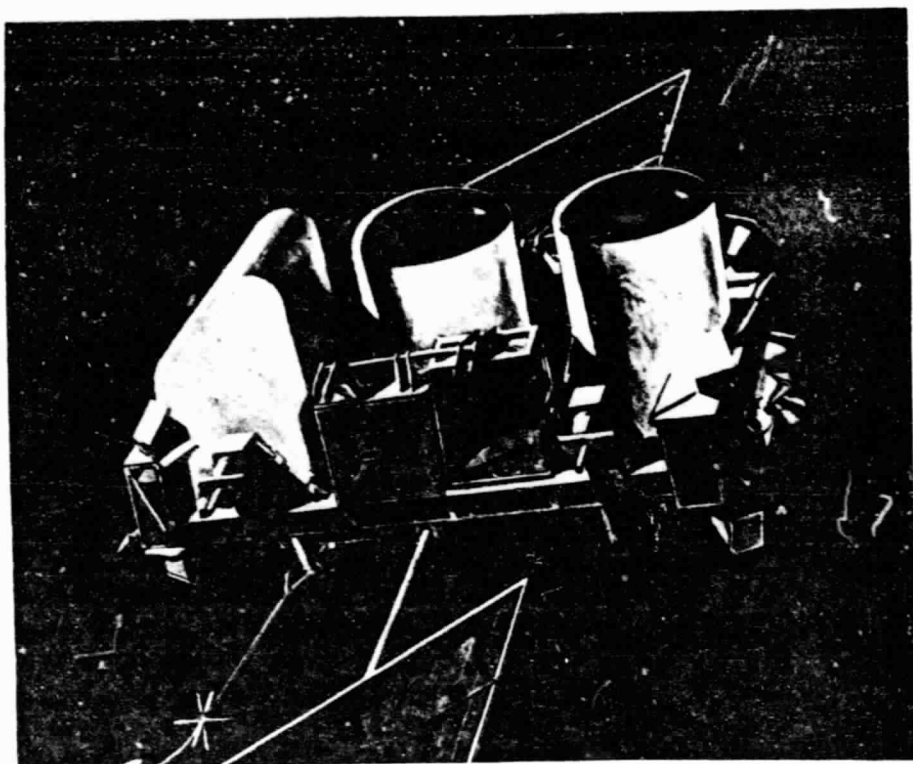


Fig. 10: An Artist Concept of the Gamma Ray Observatory  
(original Courtesy TRW)

accurate to 0.1 milliseconds to allow precise comparisons of pulsars and other time varying sources with observations at other wavelengths from ground observations and other satellites. It will carry four scientific instruments which will now be summarized.

Oriented Scintillation Spectrometer Experiment (OSSE): OSSE has been designed to undertake comprehensive observations of astrophysical sources in the 0.1 - 10 MeV energy range. Secondary capabilities for  $\gamma$ -ray and neutron observations above 10 MeV have also been included, principally for solar flare studies. The instrument utilizes four large actively-shielded and passively-collimated Sodium Iodide Scintillation detectors, with a  $5^\circ \times 11^\circ$  FWHM field of view. The large area detectors provide excellent sensitivity for both  $\gamma$ -ray line and continuum emissions. An offset pointing system modulates the celestial source contributions to allow background subtraction. It also permits observations of off-axis sources such as transient phenomena and solar flares without impacting the planned Observatory viewing program. OSSE is a joint effort of four institutions, the U.S. Naval Research Laboratory, Northwestern University, the Royal Naval College in London, and Rice University, with Dr. James Kurfess being the Principal Investigator.

Compton Telescope (COMPTEL): This instrument, which is aimed primarily at the 1 to 30 MeV range, is based on the concept of recording the signature of a two-step absorption of the  $\gamma$ -ray, a Compton collision in an upper detector

followed by total absorption in a lower detector. In the upper one, the liquid scintillator NE 213 is used, and, in the lower one, NaI(Tl) crystals are used. This system in combination with effective charged particle shield detectors, results in a more efficient suppression of the inherent instrumental background. Spatial resolution in the two detectors together with the well defined geometry of the Compton interaction permits the reconstruction of the sky image over a wide field of view ( $\sim 1$  steradian) with a resolution of a few degrees. In addition, the instrument has the capability of searching for polarization of the radiation. The instrument has good capabilities for the search for weak sources, weak galactic features, and spectral and spatial features in the extragalactic diffuse radiation.

COMPTEL is a joint effort of four institutions, the Max-Planck-Institut für Extraterrestrische Physik, the University of Leiden, the University of New Hampshire, and the European Space Agency ESTEC, with Dr. Völker Schönfelder being the Principal Investigator.

Energetic Gamma-Ray Experiment Telescope (EGRET): The High Energy Gamma-Ray Telescope, is designed to cover the energy range from 20 MeV to  $30 \times 10^3$  MeV. The instrument uses a multi-level thin-plate spark chamber system to detect  $\gamma$  rays by the electron-positron pair interaction process and measure their arrival direction. A total energy counter using NaI(Tl) is placed beneath the instrument to provide good energy resolution over a wide dynamic range. The instrument is covered by a plastic scintillator anticoincidence dome to prevent readout on events not associated with  $\gamma$  rays. The combination of high energies and good spatial resolution in this instrument provides the best source positions of any GRO instrument. For sources of moderate strength, the position should be determined to about 10 arcmin, and the stronger sources should be identified with positional accuracy of 5 arcmin. Spectra should be measurable for these sources with high accuracy. For the diffuse galactic plane emission, spatial variations in the energy spectrum should be measurable on a scale of a few degrees.

EGRET is a joint effort of four institutions, Goddard Space Flight Center, Stanford University, the Max-Planck-Institut für Extraterrestrische Physik, and Grumman Aerospace Corporation, with Drs. Carl Fichtel, Robert Hofstadter, and Klaus Pinkau being the Co-Principal Investigators.

Burst and Transient Source Experiment (BATSE): The Burst and Transient Source Experiment for the GRO is designed to continuously monitor a large fraction of the sky for a wide range of types of transient  $\gamma$ -ray events. The monitor consists of eight wide field detector modules. Four have the same viewing path as the other telescopes on GRO and four are on the bottom side of the instrument module viewing the opposite hemisphere. The arrangement provides maximum continuous exposure to the unobstructed sky. The capability provides for 0.1 msec time resolution, a burst location accuracy of about a degree and a sensitivity of  $6 \times 10^{-8}$  erg/cm<sup>2</sup> for a 10 sec burst.

BATSE is an instrument of the Marshall Space Flight Center, with Gerald Fishmar being the Principal Investigator.

For a detailed discussion of the Gamma Ray Observatory and its instruments, particularly from a scientific point-of-view, see Kniffen et al. (1981).

## (c) Space Station

NASA is now considering a Space Station which would be a manned spacecraft permanently orbiting the earth and capable of performing a variety of scientific and operational missions. Whereas the program is not yet approved, high energy  $\gamma$ -ray astronomy is certainly among the scientific disciplines which would be able to benefit very significantly from such an opportunity. With the  $\gamma$ -rays sky surveyed in some depth with the GRO, it would, for example, be possible to concentrate on the detailed features of discrete sources and to study carefully limited regions such as clouds, galactic arms, and nearby galaxies. This could be accomplished with a very large high-energy telescope with improved angular accuracy. Several groups are now considering possible approaches to building such an instrument.

## IV. CONCLUDING REMARKS

Even considering the achievements thus far,  $\gamma$ -ray astronomy is still a young, growing science, and the potential for fundamental contributions to astronomy and astrophysics in the near future is very large. With the study of astrophysical  $\gamma$ -rays, the forces of change, the formative process in the Galaxy and interstellar clouds, rapid expansion processes, explosions, the largest energy transfers, and very high energy particle acceleration are all examined directly. If the mission opportunities that have been discussed here come into being, the results that will be obtained, particularly in combination with those from other areas of astronomy, will provide an entirely new look at the Universe.

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**ADDENDUM**

Space limitations prevented inclusion of schematic drawings of the four GRO instruments in the original published version of this article. They are, however, included here on the next four pages for reference.

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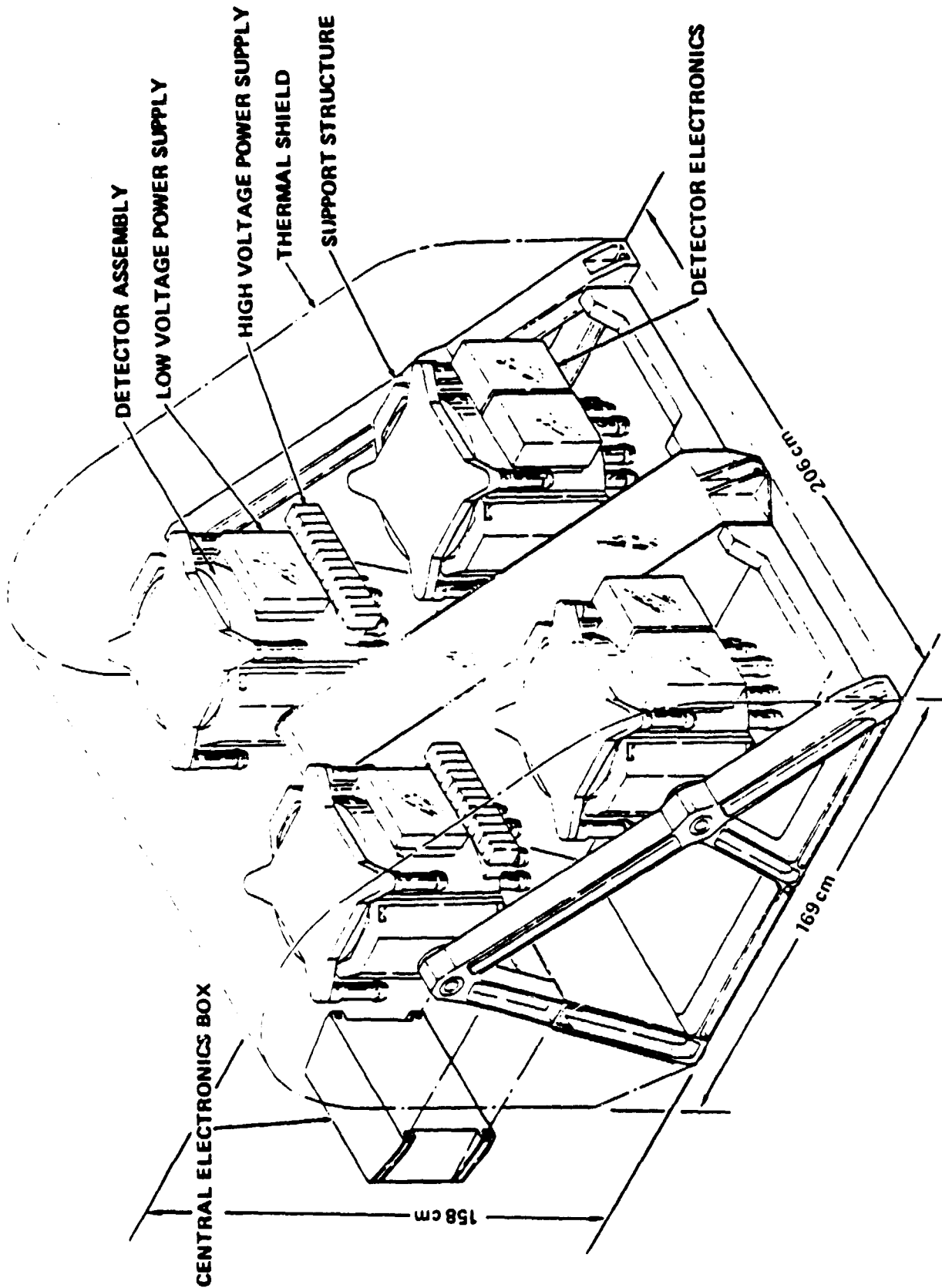


Fig. A1: The GRO Oriented Scintillation Spectrometer Experiment

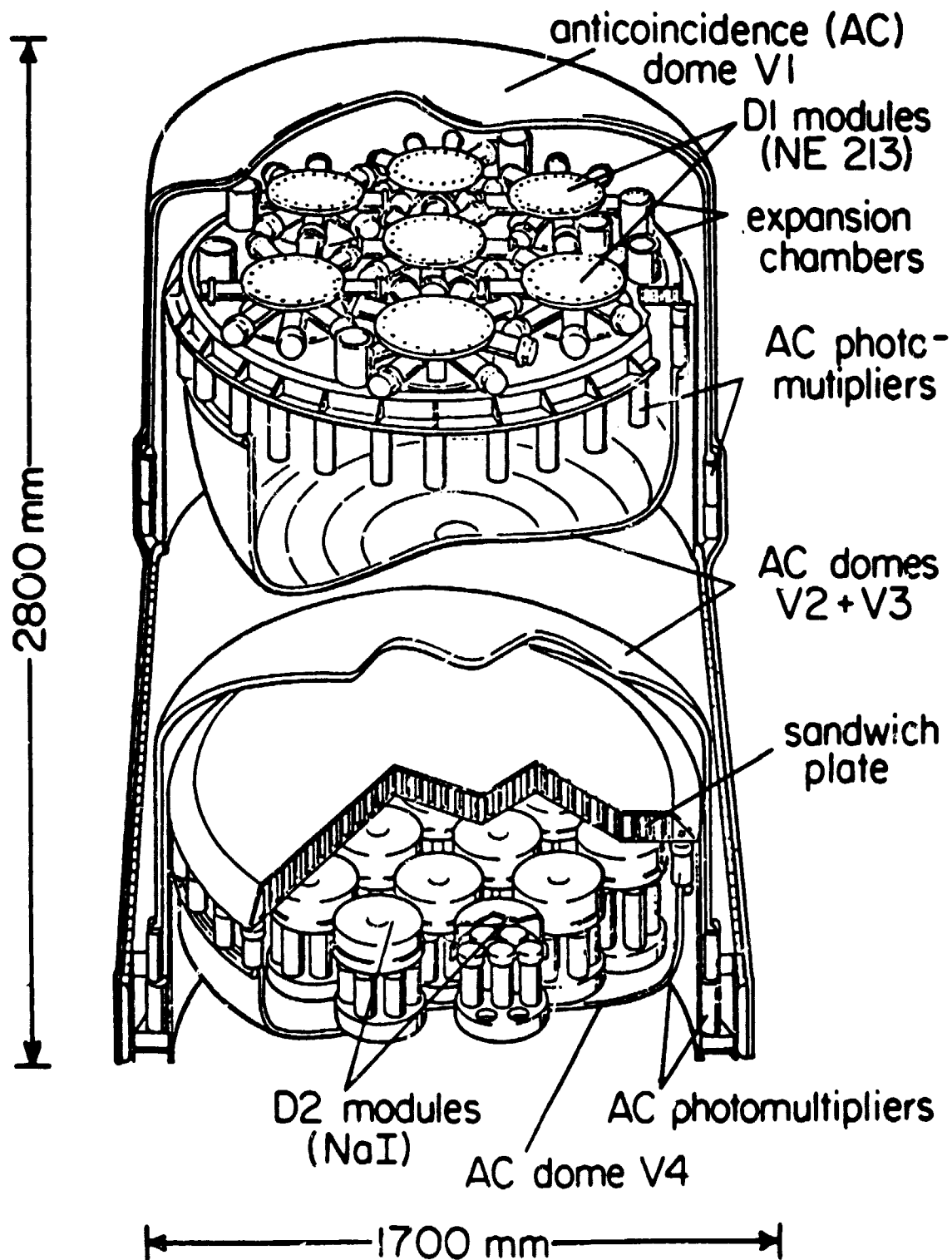


Fig. A2: The GRO Imaging Compton Telescope

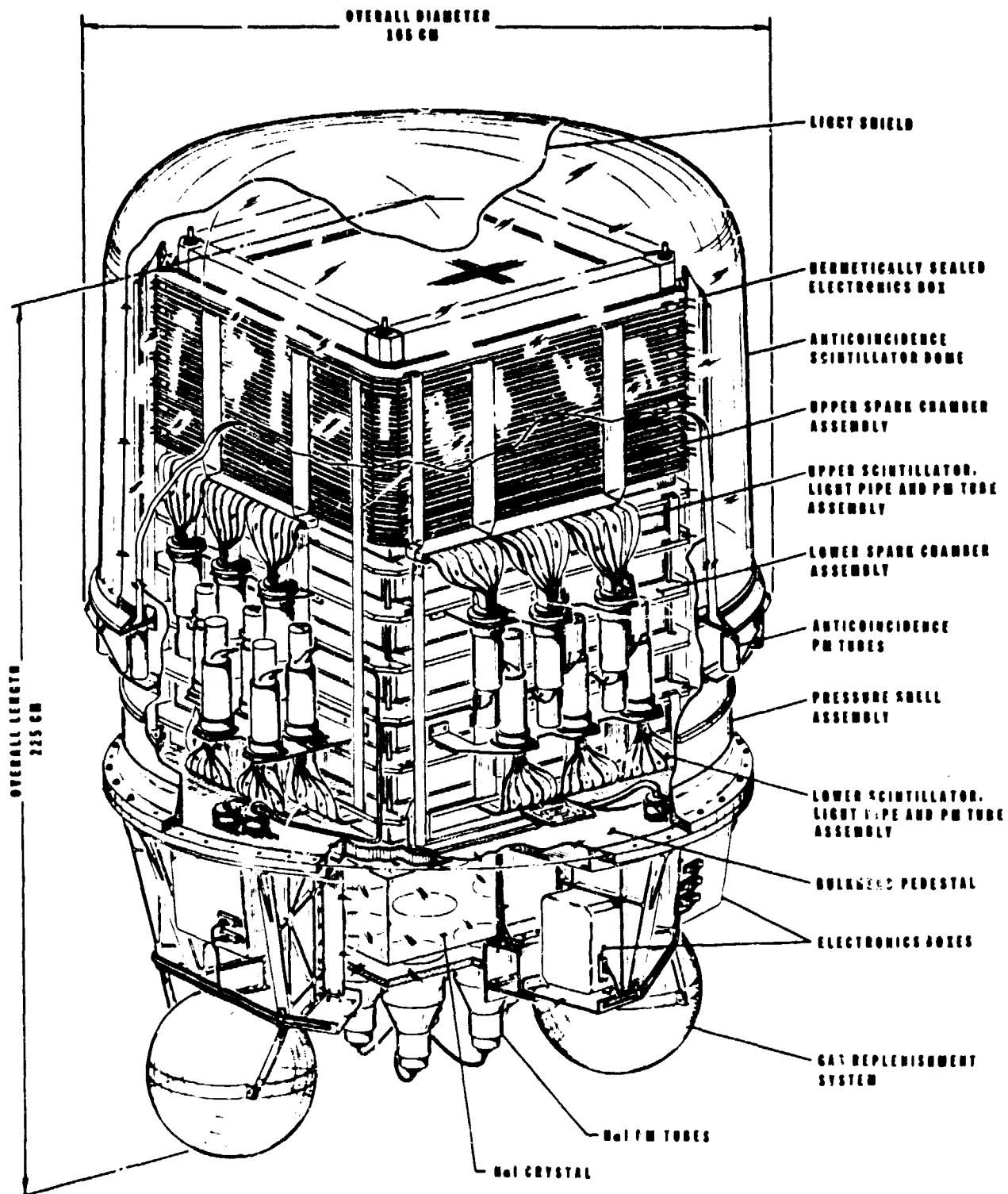


Fig. A3: The GRO Energetic Gamma Ray Experiment Telescope

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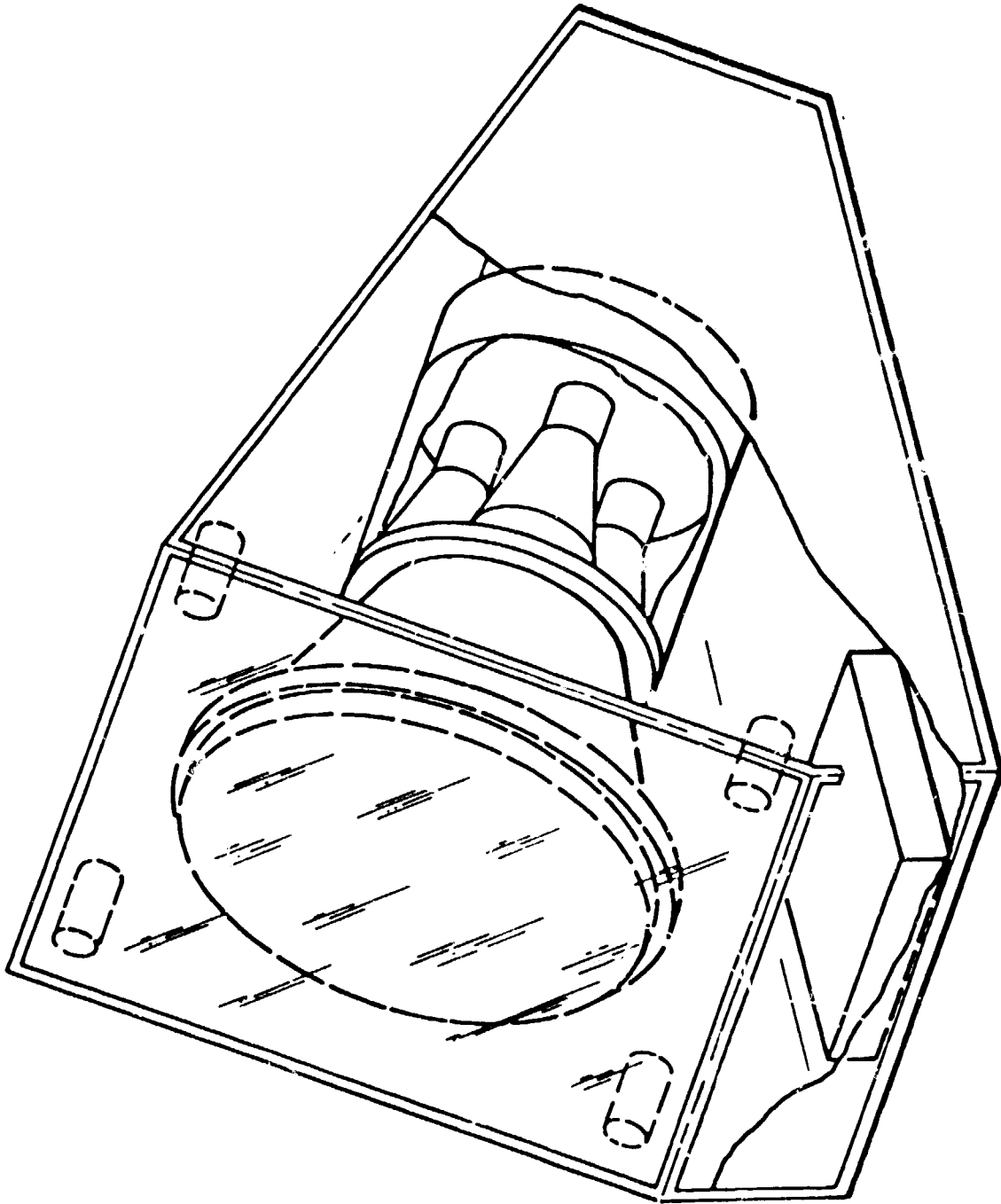


Fig. A4: Detector Module for the GRO Burst and Transient Experiment